A Growing Family of Targets for the NATIONAL IGNITION FACILITY

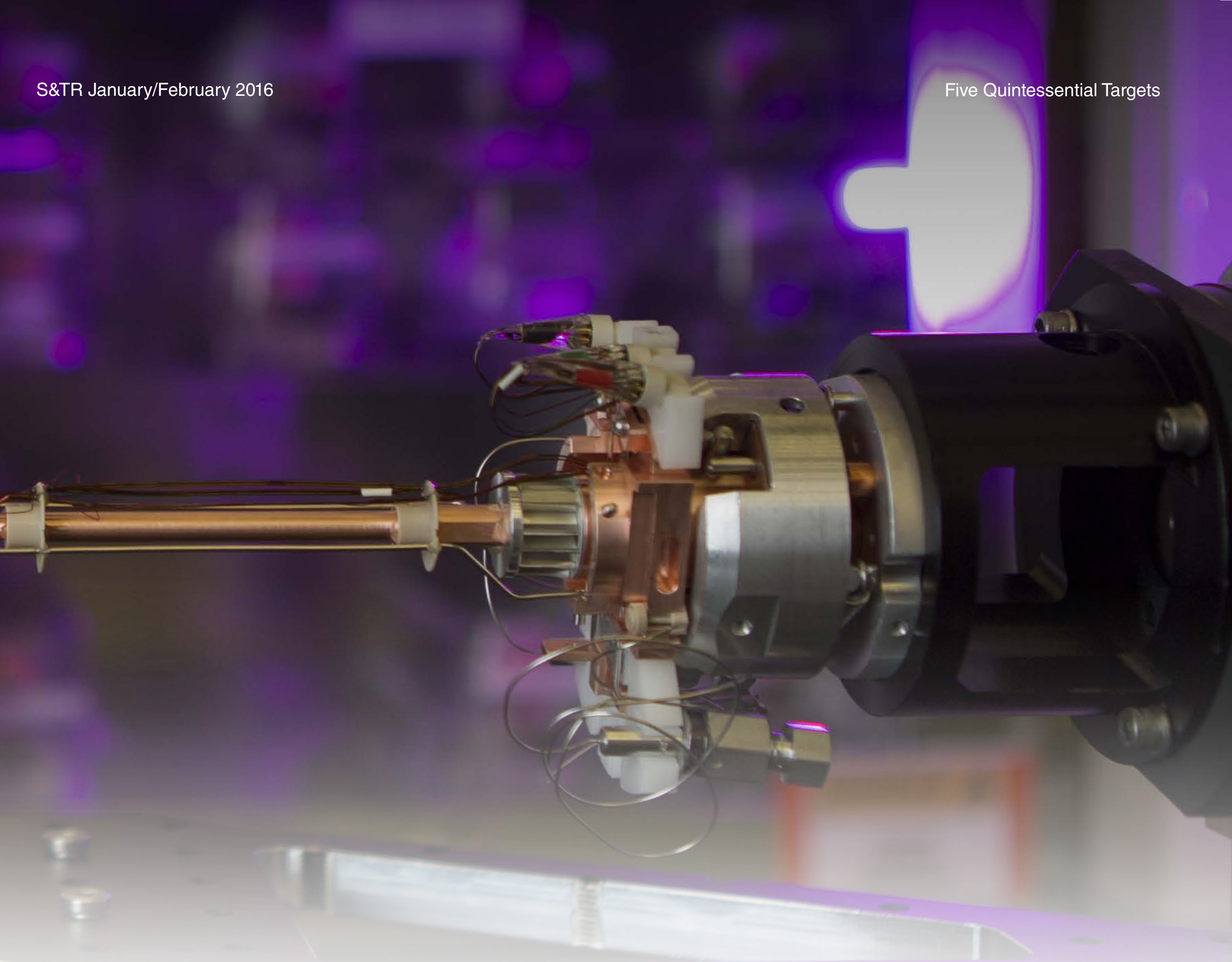
Remarkably tiny and precisely manufactured targets are enabling breakthrough physics and materials research.

IN the world of experimental physics, the National Ignition Facility (NIF) is a modern marvel—an advanced tool designed to help researchers better understand the behavior of materials under extreme pressures and temperatures. The world's most energetic laser, NIF creates temperatures greater than those of the Sun and pressures 100 billion times Earth's atmosphere, conditions similar to those in stars and detonating nuclear weapons.

NIF is the paramount experimental facility in the National Nuclear Security Administration's Stockpile Stewardship Program to ensure the continuing safety, security, and effectiveness of the nation's nuclear weapons. (See *S&TR*, July/August 2015, pp. 6–14). NIF's millimeter-scale targets, combined with associated laser pulse shapes and a vast array of diagnostics (together called a platform) also make possible breakthrough research in inertial confinement fusion (ICF), high-energy-density (HED) physics, and discovery science (in areas such as astrophysics and materials science).

NIF experiments rely on a wide variety of targets, all of which have intricate assemblies of extremely small parts. Designing, machining, and assembling these parts with micromanipulators into precisely manufactured targets requires a complex interplay among target designers, physicists, materials scientists, chemists, engineers, and technicians.

The physics package contains the main experimental components of every NIF target and may include an ablator to initiate a specific ramp of pressure, a "reservoir" of different materials to shape a compression pulse, a backlighter that creates a beam of diagnostic x rays when illuminated by laser light, a cylinder called a hohlraum to convert laser light to x rays, and a material under



investigation. However, the complete target assembly also contains shields to protect the NIF beamlines from potentially destructive back-reflected light and debris created during the shot; stalks to hold parts rigidly in position; and features to aid the proper alignment of laser beams, target, and diagnostics for an experiment.

Target components are produced by the Laboratory; General Atomics of San Diego, California; and Schafer Corporation of Livermore, California. Assembly and inspection teams are composed of experts from all three entities, and construction of the final target is conducted at the Laboratory. "Our targets are fragile, so we want them assembled close to NIF," explains target fabrication manager and physicist Abbas Nikroo. Most targets are assembled in a 334-square-meter Class 100 clean room, which limits dust to no more than 100 particles 0.5 micrometers or larger per 0.28 cubic meters of air.

About 40 percent of targets are designed for ICF experiments, another 40 percent are for HED experiments, and the rest are for discovery science and various national security programs. To increase production efficiency, engineers strive to take the artisan aspect out of manufacturing as much as possible. "We have streamlined design and production of ignition targets so the process is more like plug and play," says Nikroo.

Approximately 430 targets were manufactured from September 2014 to October 2015, and at least 190 of these had unique fabrication requirements. In contrast to standardized ICF target designs, HED target geometries and materials are always changing to meet specific experimental goals. Low-density foams with complex properties are a common feature in HED targets. By varying foam densities and compositions, target designers tailor the desired physics characteristics for each experiment. Developing novel foams of uniformly high quality that can be machined and assembled into a target is a significant manufacturing challenge.

Meeting Precise Specifications

The small-scale phenomena and extreme conditions targets encounter during experiments make the results highly susceptible to any manufacturing imperfections. Therefore, all targets must meet precise specifications for factors such as density, concentricity, thickness, uniformity, shape, roughness, internal microstructure, location of dopants, accuracy of joints and parts, and surface finish. For example, target components are typically machined to an accuracy of 1 micrometer (millionth of a meter), while some surface features cannot exceed 20 nanometers (billionth of a meter).

Many fabrication techniques, materials, and tools are derived from other industries. Chemical engineer Alex Hamza notes that target assembly processes include techniques borrowed from in vitro fertilization, in which microscopic procedures are performed on a human cell measuring about 10 micrometers in diameter, the same size as many features found on NIF targets. At the same time, new fabrication, measurement, handling, and inspection methods are developed in-house. “We can’t use tweezers because they would damage the fragile parts,” says mechanical engineer Becky Butlin, who supervises most assembly operations. Instead, technicians use pen-like devices that hold onto tiny parts with a gentle vacuum force.

Components are made from foams, plastics, crystals, gases, and metals. Fabrication capabilities include single-point diamond turning lathes, precision milling and grinding, laser micromachining, polishing, lithography, chemical vapor deposition, electro-deposition, atomic layer deposition,

A target fabrication technician uses an optical coordinate measuring machine to align a capsule inside a hohlraum for an inertial-confinement-fusion (ICF) target.

and implantation of metal impurities called dopants.

At every assembly step, workers inspect components using nondestructive methods, such as various types of microscopy, radiography, interferometry, and spectroscopy, as well as optical coordinate measurement and x-ray fluorescence to ensure precise target specifications are met.

Butlin notes that recruiting qualified staff for target fabrication is a challenge. “We look for people who have clean room and microscope experience and mechanical aptitude, but most skills must be learned on the job,” she says. To streamline the most delicate and time-consuming tasks, precision robotic stations have been installed.

Birth of a Target

To turn a sketch or idea for a new target into reality, experimenters must first discuss with target engineers the overall concept, the necessary components and materials, required specifications and parts tolerances, and the data they want to obtain. Nikroo says that early consultation is critical because materials availability as well as target fabrication and assembly challenges may affect the fabrication timeline. Target engineers determine the feasibility of fabricating and assembling the components. Importantly, Nikroo notes, “Target engineers know the limits of their manufacturing tools.”

Over several weeks, experimenters collaborate with representatives from target engineering and NIF laser alignment and operations to uncover and resolve any physics, safety, and contaminant issues. The cleanliness of NIF target assemblies must be rigorously controlled to prevent laser optics damage from plasma and debris and to avoid contaminating sensitive coatings on lenses and other optics. High-fidelity computer simulations are sometimes conducted to determine the likelihood that any debris will be generated from a new target.

Five remarkably different targets exemplify the wide range of materials and geometries a NIF target may have and the distinct physics areas they are created to address. These targets include those to determine materials strength, investigate the physics of fusion reactions, research the early stages of star formation, determine materials structures under high pressure through x-ray diffraction, and measure x-ray transmission in three dimensions.

Metals Under Pressure

A material's strength determines to what extent the material deforms when it is stretched or compressed. NIF experiments are designed to measure strength at extremely high pressures without significantly increasing the temperature of the material being tested. About a dozen such experiments are conducted yearly at pressures never achieved in a laboratory until NIF began operation.

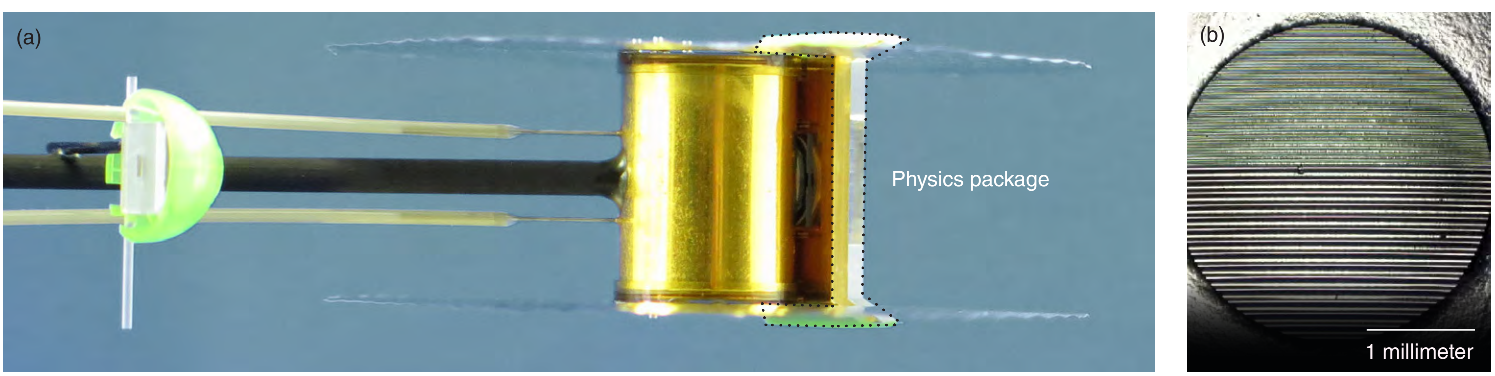
Mechanical engineer Angela Cook notes that strength and diffraction experiments (see pp. 10–11) complement each other. Both types of tests examine materials subjected to tens of millions of Earth atmospheres. The current strength-platform design was finalized after experiments were conducted first at the University of Rochester's Omega Laser Facility and then at NIF. Current targets have a production cycle of about three months, and, owing to changing experimental needs, are made only three at a time.

The target assembly features a hohlraum 9 millimeters in diameter by 14 millimeters long made from a thin film of epoxy coated inside with a layer of gold. Positioned directly over a side hole in the hohlraum is a 2-millimeter-thick, multilayered physics package containing a reservoir of five different materials, including two foams—each of a different density and diamond-turned to exact dimensions and surface finish—and an enclosed metal sample. Laser light enters the top and bottom of the hohlraum, creating x rays that ablate the reservoir and produce a pressure wave of plasma. The pressure wave unloads across a vacuum gap and through two x-ray shields of gold and plastic before impacting the metal sample. To achieve high pressures without melting or shocking the target, the reservoir is designed to carefully shape the pressure wave such that the pressure is slowly ramped up over a period of nanoseconds.

The metal samples were meticulously imprinted with two-dimensional sine-wave patterns of 1-micrometer amplitude (height) and wavelengths between 50 and 75 micrometers. Materials scientist Kerri Blobaum's team adapted a pressing technique used by the U.S. Mint to precisely stamp or "coin" the microscopic ripples into metals (see *S&TR*, September 2015, pp. 21–23). During the experiment, the imprinted ripples grow when they experience compressive pressure from the shocked reservoir as it pushes against the target. "The ripples grow at a slower rate when material strength is high," explains Cook.

About 50 to 80 nanoseconds after the initial laser pulse causes the reservoir to apply pressure to the sine-wave sample, a second laser pulse strikes a backlighter (a thin film of silver or zirconium), creating an x-ray radiography source. The backlighter's x rays are focused with a collimator and used to capture an image of the growing ripples with an x-ray imaging diagnostic.

The physics and target teams are currently developing a second experimental platform that will use NIF's Advanced Radiographic Capability (ARC), the world's highest energy short-pulse laser. In this new platform, the ARC beam strikes a backlighter foil that produces a higher energy x-ray source for improved x-ray imaging of the material under study.



(a) The target for a strength experiment features a 9-by-14-millimeter hohlraum. Positioned over a side hole in the hohlraum is a 2-millimeter-thick, multilayered physics package containing a reservoir of five different materials, gold and plastic x-ray shields, and a sample of the metal of interest. (b) The metal sample is imprinted under a microscope with two-dimensional sine-wave patterns. The imprinted ripples grow when they experience the pressure wave generated in the experiment.

Efforts Toward Ignition

In ICF experiments, laser beams strike the inside walls of a hohlraum. The resulting x rays compress a 2-millimeter-diameter capsule containing deuterium and tritium (D–T) fuel. ICF targets are extremely smooth and fabricated from plastic polymer, diamond (high-density carbon), or beryllium. The capsules may also contain internal layers with dopants that increase x-ray absorption. Precise control over dopant concentrations and uniformity is a materials challenge.

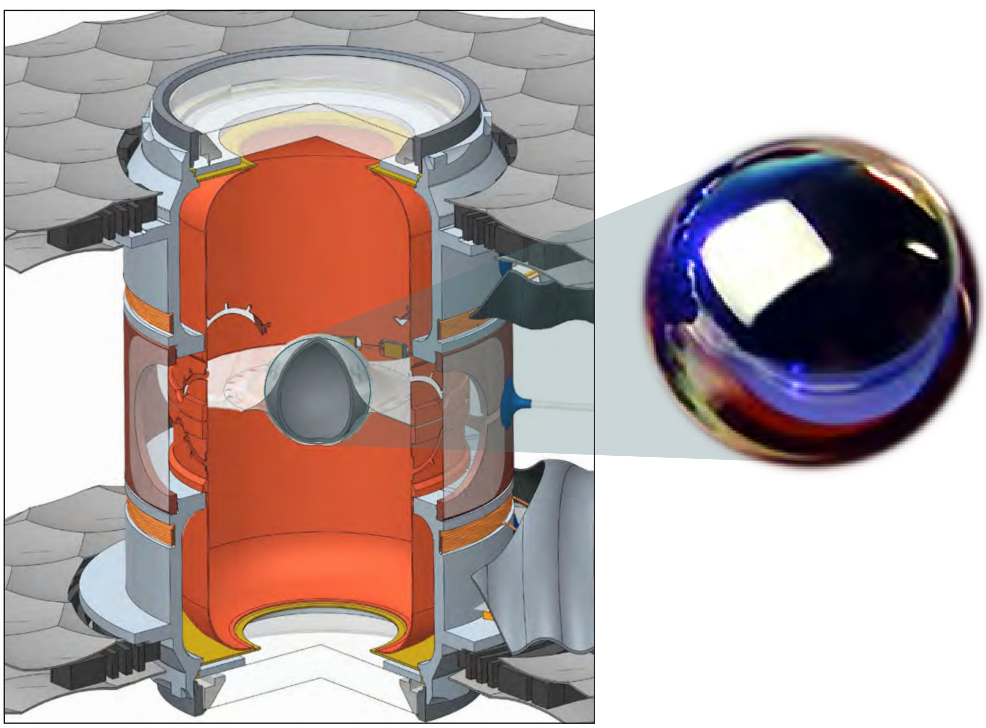
The capsule is suspended at the center of a gold hohlraum, which is approximately 30 micrometers thick, 9 millimeters high by 5 millimeters in diameter, and built in two halves. New experimental designs have increased the size of the hohlraum for more uniform implosion, while other target designs feature subscale versions. "Shots using smaller scale hohlraums require less laser energy so they cause less optics damage but still provide meaningful data," explains chemist Michael Stadermann, group leader of science and technology for target fabrication. An alternative experimental hohlraum features a liner of depleted uranium for higher conversion efficiency of laser light to x rays. Livermore scientists have also pioneered a system to supply D–T gas into the capsule through a fill hole less than 5 micrometers across, characterize the resulting cryogenic inner D–T layer, and then maintain the entire target package below 20 kelvin.

The capsule is supported in the hohlraum by a very thin plastic film called a tent. Recent experiments have shown that this tent causes a perturbation during the implosion. "The perturbation seems to scale with tent thickness for some pulse shapes, but it may not be possible to make a tent thin enough to eliminate the problem," says Stadermann. Thus, despite having reduced tent thickness from 300 to 30 nanometers, the team is looking at other support methods.

ICF targets are designed to generate fusion reactions with the eventual goal of ignition—where energy output is equal to or greater than the amount of laser energy incident on the target. Other targets are designed to diagnose experimental parameters of imploding capsules. These specialized targets provide information on shock timing, capsule implosion shape, implosion velocity, and the extent of colder D–T fuel mixing with the fuel core "hot spot."

The fuel capsule requires a precise spherical shape with surfaces smoothed to approximately 1 nanometer. Various metrology tools ensure that capsule specifications are met. For example, atomic force microscopy checks capsule shape and roughness. Phase-shifting diffractive interferometry looks for isolated defects, and precision radiography confirms capsule uniformity.

Robots have automated some time-intensive target assembly and characterization processes. "Robots save training time and improve the quality and uniformity of the target," says Stadermann. One robot installs the tents, and another inserts the hohlraum into the thermomechanical package that will keep ICF capsules extremely cold. Together, these systems save about eight hours of fabrication time per target. A new automatic proofing station for testing the cryogenic targets promises to save an additional eight hours per target.



In ICF experiments, laser beams strike the inside walls of a hohlraum 9 millimeters high by 5 millimeters in diameter and built in two halves. The resulting x rays compress a 2-millimeter-diameter capsule containing deuterium and tritium fuel. The capsule is suspended in the center of the hohlraum with remarkably thin polymer tents. (inset) ICF target capsules are extremely smooth and fabricated from plastic polymer, beryllium, or diamond (high-density carbon).

Re-Creating Eagle Nebulae

In 1995, the Hubble Space Telescope captured the famous images of the

(a) The TriStar target has three drive hohlraums, a layered foam physics package, and a radiography backlighter. The hohlraums are driven for 10 nanoseconds each in series, giving a total x-ray output lasting 30 nanoseconds. The TriStar target is designed to investigate the origin and dynamics of pillar formation such as (b) those captured from within the famous Eagle Nebula. A team of Livermore physicists led by Jave Kane and David Martinez succeeded for the first time in (c) creating pillar structures in a laboratory using a layered foam target. (Hubble image courtesy of NASA/European Space Agency/Hubble Heritage Team [Space Telescope Science Institute/Association of Universities for Research in Astronomy]).

"Pillars of Creation" in the Eagle Nebula. Twenty years later to the day, NIF researchers began conducting experiments aimed at investigating pillar formation. The team is studying whether such pillars could form from a dense cloud core in the presence of a process called ablative stabilization, which prevents the growth of traditional Rayleigh–Taylor instabilities.

In the experiments, the NIF laser is fired at a target nicknamed TriStar or QuadStar—three or four hohlraums joined together that mimic the cluster of massive stars illuminating the Eagle Nebula. To extend the duration of the high-pressure drive, the laser fires a 10-nanosecond pulse of ultraviolet light into the bottom of each hohlraum in sequence. The hohlraums measure 3 millimeters in diameter by 4 millimeters long and are driven for 10 nanoseconds each. "We want the experiment to run like a Gatling gun," says Russell Wallace, leader of the group that fabricates targets for discovery science.

The hohlraums re-radiate the light energy as x-ray pulses. These pulses then drive a shock into a layered foam cylinder and create a miniature version of a pillar that is imaged using x-ray radiography. In this way, the x rays from the hohlraums mimic a cluster of stars illuminating the Eagle Nebula. In addition, some of the NIF laser beams are directed to a 25-micrometer-thick titanium backlighter. The beams hit the backlighter's front side, generating x rays that illuminate the evolving foam plasma. A pinhole camera takes a single photograph, giving a snapshot of the evolution.

The experimental concept was tested over two years at the Omega Laser Facility. The NIF shots use larger targets and 20 times the laser energy than was possible with the Omega system. NIF is the only facility that can generate an x-ray source that is sufficiently intense, long-lasting, and directional to drive the desired flows.

Target physicists Jave Kane and David Martinez first brought Wallace a sketch of a target with material designations and general component sizes. "They had the concept and we provided the details," says Wallace. "It was a happy marriage. Target development is always an iterative process." The team turned the sketch into detailed engineering drawings, including critical NIF alignment requirements. "NIF has only a limited ability to position the target and ensure the beams are correctly pointed," he explains. For these targets, the glass rod that holds the foam cylinder also provides a key element used for aligning the target.

As part of the target design phase, the team had to examine the possibility that debris generated by the experiment could damage diagnostic instruments or optics. This process also involves resolving any issues with unconverted light, which can travel back up the beamline and damage optical components. Finally, the target design process clarifies the target subcomponents and the level of complexity required for their manufacture. The foam components had the most demanding requirements for these targets but were successfully built using target technologies developed and refined over the years.

Tracking Radiation

Radiation transport, the flow of x rays through materials, is an important property used to validate supercomputer codes for stockpile stewardship as well as to understand the formation of stars and the heating of ICF capsules. With radiation transport targets, researchers investigate how high temperatures affect radiation flow through a material at the speed of sound and greater.

Historically, radiation transport experiments have measured flow in a two-dimensional geometry. However, current designs utilize a nested silica (silicon dioxide) and tantala (an oxide of tantalum) hemispherical foam target to measure radiation flow in three dimensions. Three-dimensional measurements required new glass tube or “light pipe” diagnostics because traditional Velocity Interferometer System for Any Reflector (VISAR) diagnostics do not work in an arc geometry.

Mechanical engineer Danielle Doane says the challenges associated with these targets include synthesis of low-density foams and exact interference press fits. The target is a complex assembly of millimeter-scale parts with micrometer tolerances. The foam construction contains nested shells of 0.125-grams-per-cubic-centimeter tantala only 0.10 millimeters thick. The middle silica foam has a density of 0.045 grams per cubic centimeter and is 0.64 millimeters thick. The inner tantala foam has a density of 0.125 grams per cubic centimeter and a thickness varying from 0.15 to 0.35 millimeters.

The targets require about three months to build, including eight weeks for foam machining, which involves micromilling and diamond turning. The foams are machined on a 5-axis micromill with tool diameters down to 25 micrometers to produce a few hundred micrometer-level surface finish. The three different nested foam layers are pushed together with an interference fit to attain an adhesive-free interface.

The foam subassembly is suspended with a tent inside a two-part hohlraum. Several light pipes are inserted at specific angles and positions to allow the transmission of x-ray signals from the target to diagnostics. Coated with gold on the inside, the light pipes are inserted using precision stages and view ports in the hohlraum for positioning accuracy. Final target fabrication involves gluing the nested foam assembly to a top washer, then gluing the bottom half of the hohlraum to the top half, and ultimately inserting the top light pipes.

During experiments, laser beams enter the hohlraum from underneath, strike its walls, and generate x rays that turn the foam to plasma. Instruments record the movement of radiation flowing out of the hohlraum. Radiation transport experiments using these targets were first conducted on the Z machine at Sandia National Laboratories and at the Omega Laser Facility. More than a dozen targets with slight variations have been tested at NIF.

Targets for Diffraction Studies

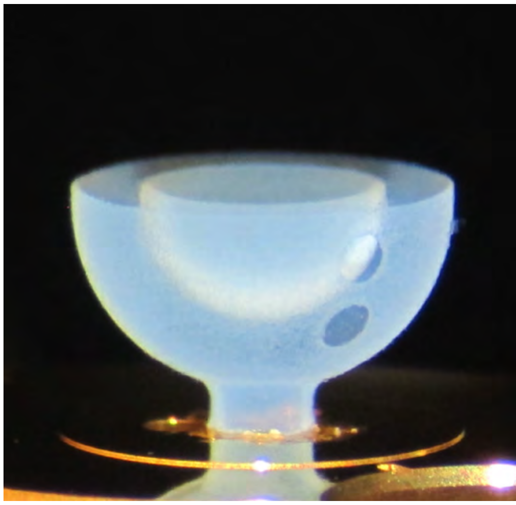
X-ray diffraction experiments probe the atomic structure of a material and thus identify its crystallographic phase (for example, face-centered or body-centered cubic—wherein the unit cell is cube-shaped). Specialized targets enable diffraction to be performed at extremely high pressures. Similar to strength experiments, diffraction studies require that the sample does not melt before the desired pressure is reached.

The experiments, called TARDIS (Target Diffraction In-Situ), are the first to include a NIF target and diagnostic on a single, integrated platform. The TARDIS target has a tantalum–tungsten alloy body, which houses the material sample; an x-ray backlighter mounted on a stalk; and a semicircular diagnostic cartridge containing image plates to capture the x-ray diffraction pattern.

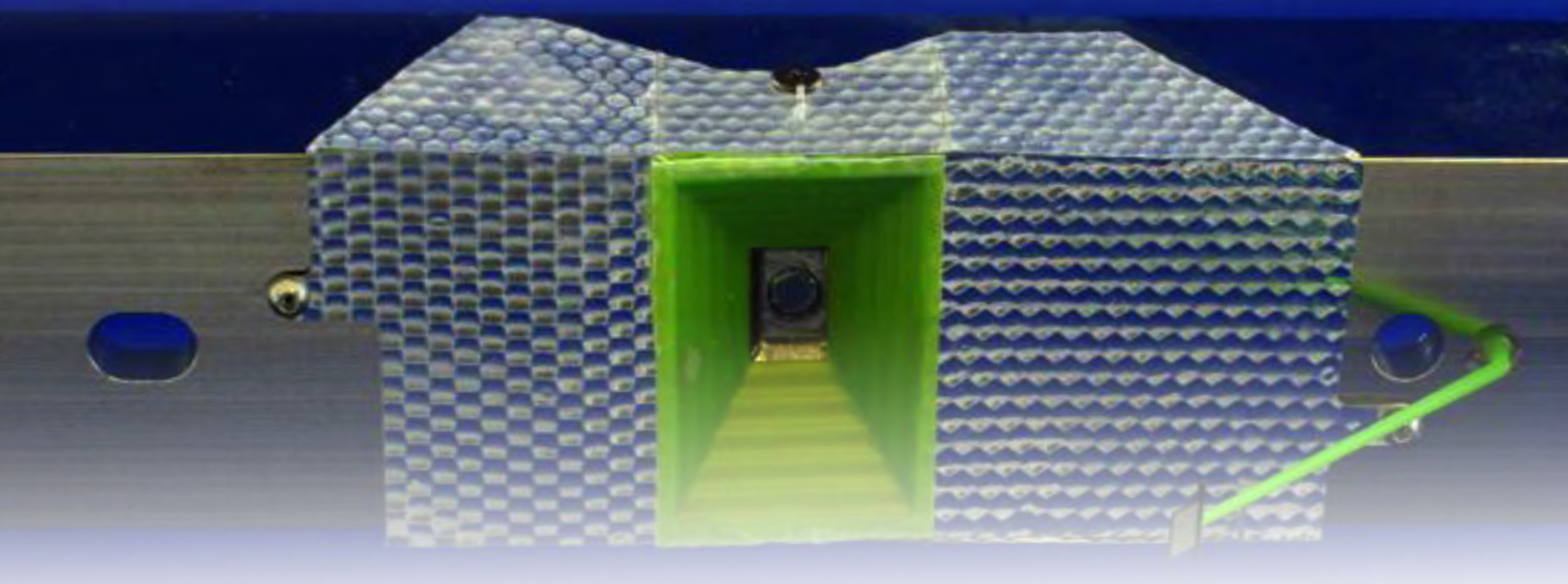
TARDIS experiments provide important information on the properties of materials at high pressures for stockpile stewardship applications. They are also designed to provide insight into phase changes, or structural transitions, that occur in materials under pressures comparable to those believed to exist in the cores of extrasolar planets many times more massive than Earth.

Each target contains a selected material some 4 to 8 micrometers thick and 2 to 3 millimeters in diameter sandwiched between two thin, single-crystal diamonds polished to exact specifications. A third diamond, coated with 2 micrometers of gold, is added to the sandwich, and the laser pulse strikes this diamond ablator.

As in strength experiments, an initial laser pulse generates pressure on the sample, and nanoseconds later, additional laser beams hit the backlighter (germanium on carbon) to generate diagnostic x rays. When the initial laser light strikes the diamond ablator, the sample is ramp-compressed and held at constant pressure



Radiation transport targets use nested, hemispherical foams to measure radiation flow in three dimensions. Glass tubes or “light pipes” are inserted through holes in the foam (seen here) to allow the transmission of x-ray signals from the target to diagnostics.



TARDIS (Target Diffraction In-Situ) experiments use x-ray diffraction to probe a material's atomic structure. The TARDIS package has a tantalum and tungsten target body, which houses the material sample; an x-ray source target mounted on a stalk; and a semicircular diagnostic cartridge containing image plates to capture the x-ray diffraction pattern of the sample.

and temperature. The diagnostic x rays are collimated by a 400-micrometer pinhole before being diffracted by atomic layers in the sample. The crystal diffraction lines are recorded onto image plates. The resulting diffraction pattern serves as a "fingerprint" for the crystallographic structure (phase) of the sample material under pressure.

The shots permit phase transitions to be studied in a wide variety of materials, such as carbon, iron, lead, tantalum, platinum, and uranium. Researchers control the pressure by the number of laser beams and the beams' energies. Approximately 30 experiments have been conducted, all at pressures greater than 1 megabar. Blobaum says, "We are learning about the structure of materials at conditions never previously achievable."

The stringent thickness requirements for the targets' thin metal, diamond, and glue layers present significant manufacturing and inspection challenges. In response, target fabrication engineers have developed double-sided white-light interferometry to profile both sides of a part simultaneously and ensure it meets specifications. "We want the laser drive to be planar, so the metal and diamond layers must be uniformly flat and parallel," says Blobaum. In addition, alignment features on the TARDIS assembly help to precisely position the laser beams onto the sample.

Meeting Increasing Demand

As NIF's shot rate has increased, so too has the demand for targets. Despite the challenges involved in designing, manufacturing, and testing custom-made, precision-engineered targets, the fabrication and assembly teams are satisfying the need, with annual production predicted to grow from 430 to 480.

Nikroo notes that engineers have established faster fabrication and assembly methods, including modular and batch processing to speed deliveries and reduce nonuniformities. "We are making a big push to reduce the hours it takes to assemble a target," says Butlin. Installing robotics into the assembly process is part of this effort.

The target fabrication team is also researching innovative techniques to position the D–T capsule in the center of the hohlraum without the thin polymer tent for ICF experiments. Other challenges with ICF targets include fabricating depleted uranium hohlraums without gold liners, adding a silicon dopant to diamond capsules without creating excessive levels of silicon carbide, and avoiding nonuniform oxygen uptake in fuel capsules. With an eye on increasing data and extending experimental regimes, engineers are beginning to design double backlighters, which would capture two experiments' worth of data in a single target shot. With demand for NIF and its targets growing, experimentalists rise to the challenge of designing new and improved targets as scientists, engineers, and technicians endeavor to efficiently make them.

—Arnie Heller

Key Words: Advanced Radiographic Capability (ARC), backlighter, diffraction, Eagle Nebula, foam, high-energy-density (HED) physics, hohlraum, inertial confinement fusion (ICF), materials science, National Ignition Facility (NIF), Omega Laser Facility, radiation transport, ramp compression, TARDIS (Target Diffraction In-Situ), Velocity Interferometer System for Any Reflector (VISAR), Z machine.

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